High-Resolution X-Ray Spectroscopy: What Will *AXAF* Tell Us about Stellar Coronae?

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Abstract. I present a simulation of the soft X-ray spectrum of the well-known active binary Algol (β Per) as it is predicted to appear in a 50 kilosecond exposure using the *AXAF* CCD Imaging Spectrometer (ACIS) detector and High Energy Transmission Grating (HETG) combination. I discuss the capabilities of *AXAF* that should enable it to resolve the ongoing debate about the non-solar coronal abundances inferred from analyses of much lower resolution *ASCA* spectra of Algol and other active stars. I also give examples of the types of analyses that may be usefully applied to *AXAF* grating spectra, and discuss the known limitations of the present atomic data and coronal plasma emission codes.

1. Introduction

One of the most interesting findings in the field of stellar coronae in recent years is that their low- (e.g. *ROSAT* PSPC) and moderate-resolution (e.g., *ASCA* SIS) X-ray spectra cannot in general be well-fit by coronal plasma models having solar photospheric (hereafter solar) abundances (cf. Drake 1996 for a brief review). In many cases, particularly for the most active stars such as RS CVn binaries, the most striking anomaly is that Iron appears to be deficient by a factor of 3-10 relative to the solar value (e.g., Ortolani *et al.* 1997, Mewe *et al.* 1997). Other heavy elements also are generally apparently underabundant relative to their solar values, by amounts that vary from star to star. These apparent anomalous abundances were initially suspected by some in the field to be artifacts. Various explanations were put forward, including: (i) they are due to an inadequate treatment of the temperature distribution of the coronal plasma; (ii) they are due to opacity effects in the strong resonance lines of the abundant elements such as Fe, Si and Mg; (iii) they are due to an additional power-law continuum 'diluting' the lines; (iv) they are due to inadequacies in the atomic physics contained in the standard coronal plasma models of Raymond & Smith (RS) or Mewe & Kaastra (MEKA); or (v) (in some cases) they are due to instrumental effects, e.g., the response matrices not being completely accurate in certain spectral regions.

The consensus of recent work is that, although there are specific cases in which some of the non-intrinsic explanations may apply, the general conclusion that the abundances in many coronae are really non-solar is hard to avoid. In retrospect, this probably should not have been a big surprise since (i) not all stars have photospheric abundances identical to the Sun's, and, in particular, the Sun appears to be metal-rich by about 0.2 dex compared to the average of various types of stars in the solar neighborhood (even stranger, many active binaries, although they have Pop I-type kinematics, appear to be metal deficient by 0.3-1.0 dex compared to the Sun, although the reality of these photospheric abundance anomalies is still being debated), and (ii) most high-resolution EUV and soft X-ray studies of the solar coronae have derived coronal abundances that differ significantly from their photospheric values, with the most common finding being an overabundance of low-FIP (first-ionization potential) elements such as Fe and Mg relative to high-FIP elements such as Ne (see reviews by Feldman 1992 and Meyer 1996).

2. The Capabilities of *AXAF*

The SIS detectors on *ASCA* have a spectral band-pass from 0.5 to 10 keV, roughly, with a spectral resolution increasing from 50 to 150 eV over this range. With this resolution the Fe L-shell complex is completely unresolved and blended with, for example, the He-like and H-like complexes of Ne and Na, and the L-shell complex of Ni. In my opinion, the elements for which *ASCA*-derived abundances are reliable are O (0.57 & 0.65 keV), Mg (1.35 & 1.47 keV), Si (1.86 & 2.01 keV), S (2.46 & 2.62 keV), Ar (3.14 & 3.32 keV), Ca (3.90 & 4.10 keV), and Fe (6.70 & 6.97 keV), where I have listed the energies of the resonance line of the He- and H-like ions of these elements, and assuming that there is sufficient signal-to-noise in the spectrum at these energies to significantly detect these lines. Although the He-like and H-like resonance lines of N at 0.43 keV and 0.50 keV lie on the edge of the SIS bandpass, they do not appear to yield reliable abundances due to the difficulty of getting an accurate calibration in this region where the effective area is rapidly decreasing.

In contrast, *AXAF* will have much improved capabilities compared to previous X-ray telescopes in almost every instrumental parameter. Its exquisite spatial resolution ($\leq$ 1") compared to previous X-ray missions, combined with its large effective area and bandpass ($\geq$ 100 square cm in direct imaging mode using ACIS over a broad bandpass from 0.15 to 8 keV or 1.6 to 80 Å), will prove very useful for many classes of observations, e.g., those of extended objects or in crowded fields, where CCD-type spectral resolution ($E/\Delta E \sim 10 - 60$) is adequate. For observations in which imaging capabilities are of secondary importance, the insertion into the light path of transmission gratings enables a spectral resolution $E/\Delta E \sim 100 - 1500$ to be achievable over the above-quoted bandpass: this translates to a velocity resolution of 200 km/sec at the lowest energies of 0.15 keV, notice. A more typical spectral resolution of ~ 300 is reached by the HETG gratings over the 0.6 - 1.5 keV (8 - 20 Å) range occupied by the Fe L-shell complex (this instrument combination has 10 to 100 square cm effective area, notice): thus at 1 KeV, the energy resolution will be about 3 eV, sufficient to resolve much although not all of the severe line blending in this spectral region that has not hitherto been resolved by non-solar X-ray telescopes.

AXAF has effective area in the soft (0.1 to 0.5 keV) X-ray band, and this will mean that, not only for N but also for C, the He-like and H-like features (at 0.31 & 0.37 keV for C) will be easily detectable (and resolvable using the LETG). Using the gratings will enable the Ne He-like and H-like features at

0.92 & 1.02 keV to be readily resolved. Other elements with lines in the *AXAF* bandpass which may be isolated for the first time in stellar X-ray spectra include Ni, Na, and Al, although the low cosmic abundances of the latter 2 elements would require very deep exposures for them to be detected. Thus, in the best *AXAF* spectra, we may be able to detect spectral lines and infer abundances for 10 even-Z and 3 odd-Z elements, compared to the 7 even-Z elements accessible to *ASCA*. Furthermore, these 13 elements are about equally divided between those having low First Ionization Potential (FIP), (Na, Mg, Al, Si, Ca, Fe and Ni), and those having high FIP (C, N, O, Ne, and Ar) or intermediate FIP (S).

3. Sample Atomic Physics Problem Addressable Using *AXAF*

The He-like resonance line complexes of the abundant ions such as O, Ne, Mg, and Si are in the spectral region accessible to the ACIS HETG and should also be detectable in a reasonable exposure time. The structure of these line complexes has been studied for at least 3 decades (e.g., Gabriel 1972), and the basic atomic physics parameters such as f-values and collisional strengths are well-determined. The strongest features in a He-like multiplet are the resonance (R) and the forbidden line (F) components, with the intercombination line (I) several times weaker: there are also a score of even weaker satellite lines scattered around (and blending with) the stronger lines.

What can be deduced from such complexes when the individual line components are spectrally resolved?

• One can derive accurate differential emission measures (DEMs) at the peak formation temperatures of these ions from the overall line fluxes with much less confusion than in lower-dispersion spectra where, in some cases (e.g., Mg XI), blending with other ion lines is a problem;

• From the ratio F/I, one can derive electron densities (e.g., Gabriel & Jordan 1969) provided that the density is above the critical low-density limit N_C for that particular ion (e.g., for O VII and Mg XI, $N_C \sim 3 \times 10^{10}$ and 10^{12} cm^{-3}, respectively);

• From the ratio (F+I)/R or F/R, one can derive information about possible resonance-line optical depth (τ) effects and/or (possible in flares, probably not in quiescent coronal conditions) non-ionization equilibrium effects;

• By combining the previous items, one can derive constraints on the spatial scale of the emission region.

(Notice that the above information will enable one to confirm or refute several of the proposed non-intrinsic explanations for the anomalous coronal abundances.)

Another important set of lines to study are the Fe L-shell lines in the $9-18$Å range. It has been realized, partially based on the failure of current plasma codes to fit parts of this spectral range, that there is something missing or erroneous in the line lists in this spectral region that are incorporated in these codes. Some updating of the plasma codes has already occurred (e.g., the 'new' MEKAL code includes updated L-shell spectra calculated by Liedahl *et al.* 1995), but more still remains to be done: e.g., Liedahl & Brickhouse (1998) and Brown *et al.* (1998) have convincingly argued the omission from the plasma codes of the ensemble of high-n transitions of the various Fe ions in this range is one of the causes of the mismatch between observed and predicted spectra. New laboratory data and theoretical calculations are now available for some of the Fe ions (e.g., Fe XVII by Brown *et al.* 1998 and Fe XXIV by Savin *et al.* 1996) and data for more ions should become available in the next year or so. Comparison of the lines in this region of coronal spectra with laboratory plasma spectra and theoretical predictions will be an important test of this new atomic physics, particularly for the ions Fe XXI - XXIV that are predicted to have strong lines in the relatively high-temperature coronae of these two active binaries. For those L-shell lines for which reliable atomic parameters are available and for which sufficient signal-to-noise can be obtained, DEM's, temperatures, optical depths and electron densities can be derived in an analogous manner to the He-like ions.

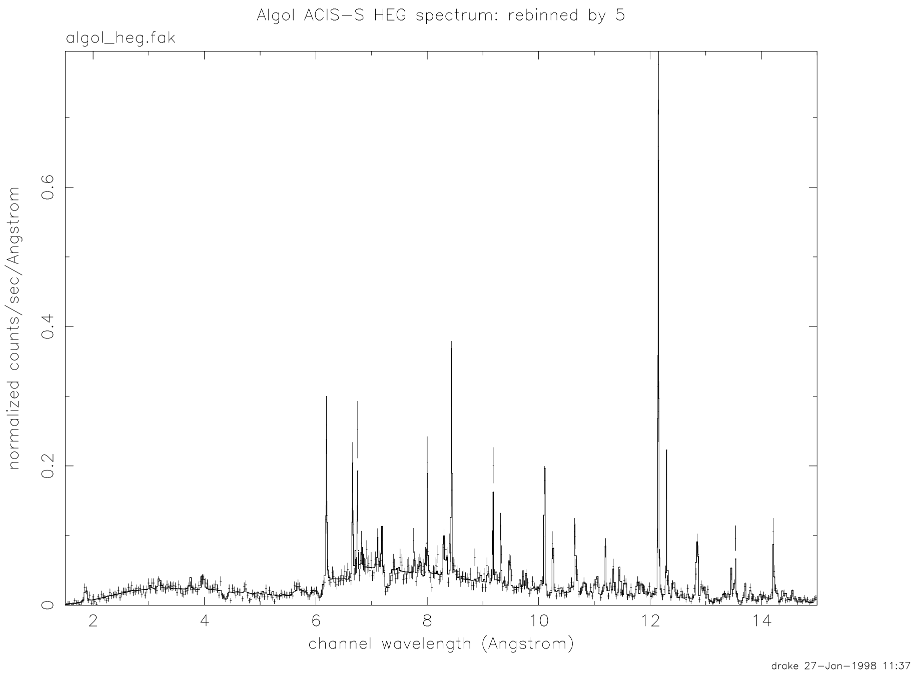

Figure 1. The complete 1.5 to 15Å ACIS-S/HEG spectrum of Algol

In Figs. 1 and 2 I show simulated Algol ACIS-S/HEG spectra integrating over 50 ksec of exposure time; I have done simulations in XSPEC using the standard coronal codes, which of course include assumptions (e.g., optically thin lines, low-densities, etc.) that such observations are in fact going to confirm or refute. The input model was based on the best-fit 2-T model to the *ASCA* spectrum of Algol presented by Singh *et al.* (1995). In Fig 1, I show an overview of the 1.5 to 15Å spectral range. Notice the wealth of emission lines (the strongest predicted line is the Ne X Lyman α line and the shortest-wavelength detected line is the Fe XXV He-like multiplet at 1.85Å), as well as the well-exposed continuum. In Fig. 2 I show a blow-up of the predicted HEG spectrum of the Mg XI He-like complex: notice that the R, I and F components are all well-resolved and significantly detected (as they also are in the Ne IX and Si XIII He-like multiplets). The prominence of the other He-like multiplets is predicted to be

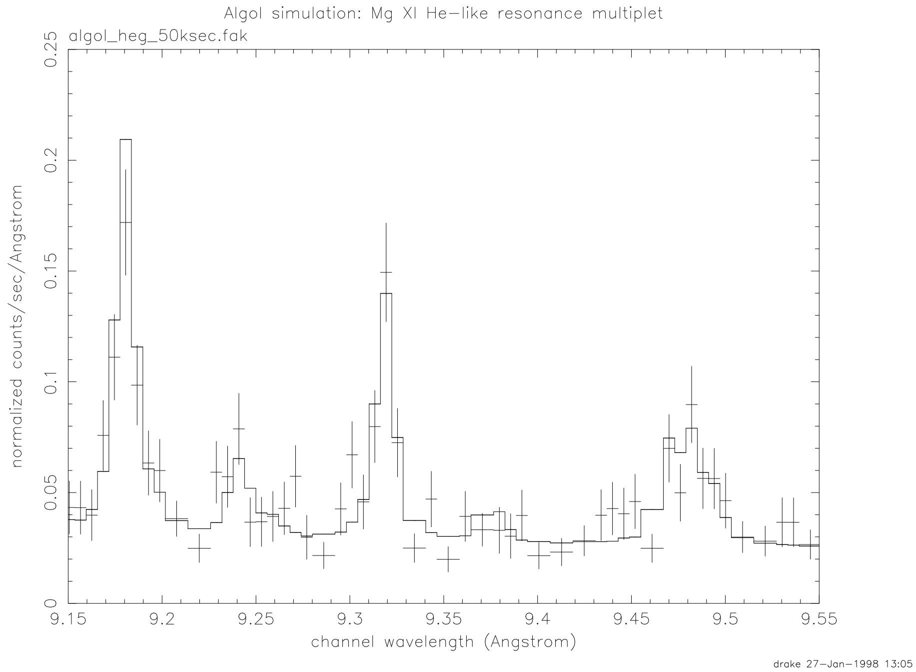

Figure 2. The Mg XI R (9.18Å), I (9.24Å), and F (9.32Å) He-like resonance multiplet region of the ACIS-S/HEG spectrum of Algol

less, being dependent on the existence of a low-temperature tail to the DEM (for O VII 21.6Å) and on the particular values of the abundances adopted for this simulation (for S XV 5.04Å, Ar XVII 3.95Å, and Ca XIX 3.18Å), and only the R components of these multiplets may be detectable.

4. The Crystal Ball

I expect that initial analyses of the *AXAF* grating spectra will be on a line-by-line basis and that a global fitting approach will not be used to model them, given that both the data and the models are being tested. Ultimately, when the model plasma codes are both complete and reliable enough, at least for the stronger lines, it may be possible to perform XSPEC- and SPEX-type global fitting approaches; this will be of great assistance in identifying the weaker lines in the grating spectra.

In a more speculative vein, I offer some predictions on some of the major things that *AXAF* will reveal about stellar coronae: (i) the non-solar abundances inferred for most stellar coronae by *ASCA* and *EUVE* will be confirmed; (ii) most coronae will exhibit complex temperature and density structure; (iii) particularly during flares, coronal lines will exhibit detectable velocity shifts and turbulent broadenings; (iv) some strong resonance lines will show evidence for high optical depths; and (v) *AXAF* and the (shortly to follow) X-Ray Multi-Mirror Mission (*XMM*) will revolutionize the field of stellar coronae in the same way that *IUE* had revolutionizing effects on the field of stellar chromospheres and transition regions. I hope to verify some of the above predictions in my forthcoming *AXAF* observations of the active binary systems Algol and UX Ari.

5. Acknowledgements

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